Los Alamos NATIONAL LABORATORY EST.1943

LA-UR-14-25784
Approved for public release; distribution is unlimited.

Title: Determining x-ray spectra of radiographic sources with a Compton spectrometer

Author(s): Gehring, Amanda Elizabeth; Espy, Michelle A.; Haines, Todd Joseph; Hunter, James F.; King, Nicholas S. P; Manard, Manuel J.; Merrill, Frank Edward; Morgan, George Lake; Sedillo, Robert; Trainham, Clifford; Urbaitis, Algis V.; Volegov, Petr Lvovich

Intended for: SPIE Optics + Photonics, 2014-08-17/2014-08-21 (San Diego, California, United States)

Issued: 2014-09-26 (rev.1)

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer,is operated by the Los Alamos National Security, LLC for the National NuclearSecurity Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Departmentof Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Determining x-ray spectra of radiographic sources with a Compton spectrometer

Amanda E. Gehring*[a], Michelle A. Espy[a], Todd J. Haines[a], James F. Hunter[a], Nick S. P. King[a], Manuel J. Manard[a], Frank E. Merrill[a], George L. Morgan[a], Robert Sedillo[a], Rusty Trainham[b], Algis V. Urbaitis[a], Petr Volegov[a]

[a]Los Alamos National Laboratory, Los Alamos, NM, USA 87545; [b]National Security Technologies, LLC, Special Technologies Laboratory, 5520 Ekwill St., Santa Barbara, CA USA 93111

ABSTRACT

Flash radiography is a diagnostic with many physics applications, and the characterization of the energy spectra of such sources is of interest. A Compton spectrometer has been proposed to conduct these measurements. Our Compton spectrometer is a 300 kg neodymium-iron magnet constructed by Morgan et al[1], and it is designed to measure spectra in the <1 MeV to 20 MeV range. In this device, the x-rays from a radiographic source are collimated into a narrow beam directed on a converter foil. The forward-selected Compton electrons that are ejected from the foil enter the magnetic field region of the spectrometer. The electrons are imaged on a focal plane, with their position determined as a function of their energy. The x-ray spectrum is then reconstructed. Challenges in obtaining these measurements include limited dose of x-rays and the short pulse duration (about 50 ns) for time-resolved measurements. Here we present energy calibration measurements of the spectrometer using a negative ion source. The resolution of the spectrometer was measured in previous calibration experiments to be the greater of 1% or 0.1 MeV/c[1]. The reconstruction of spectra from a bremsstrahlung source and Co-60 source are also presented.

Keywords: Compton spectrometer, x-ray spectrometry, gamma ray spectrometry

1. INTRODUCTION

A Compton spectrometer has recently been refurbished and re-commissioned for the purpose of measuring flash radiographic sources. Radiographic sources are employed throughout the DOE complex, including the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at Los Alamos National Laboratory and the Radiographic Integrated Test Stand (RITS-6) at Sandia National Laboratory. These sources produce intense bursts of x-rays with doses of several hundred rad at 1 m. The bursts are short, about 50 ns in duration. The characterization of the x-ray spectra of these machines aids in the analysis of the produced images and in the development and understanding of the physics of the sources.

2. METHODOLOGY AND MAGNET DESIGN

The Compton spectrometer was designed and built by Morgan et al[1] in the early 1990's. A schematic and a photograph of the spectrometer are shown in Figure 1. X-rays from a source are narrowly collimated into a beam incident upon a conversion target. The ejected Compton electrons are selected by a 1.4 cm diameter graphite collimator with an angular acceptance within 1° of the forward scattering angle. The electrons then enter the spectrometer.

The spectrometer consists of neodymium-iron permanent magnets and iron pole pieces. The assembly resembles half of a quadrupole magnet with a steel plate replacing the missing half of the quadrupole. The steel plate acts as a magnetic mirror. This arrangement is like the "achromatic mirror" described by Enge[2]. A non-uniform magnetic field is produced. The magnetic field increases linearly from the mirror plane, and a recent measurement of the field yielded a gradient of 632 G/cm with average field strength of ~6 kG.

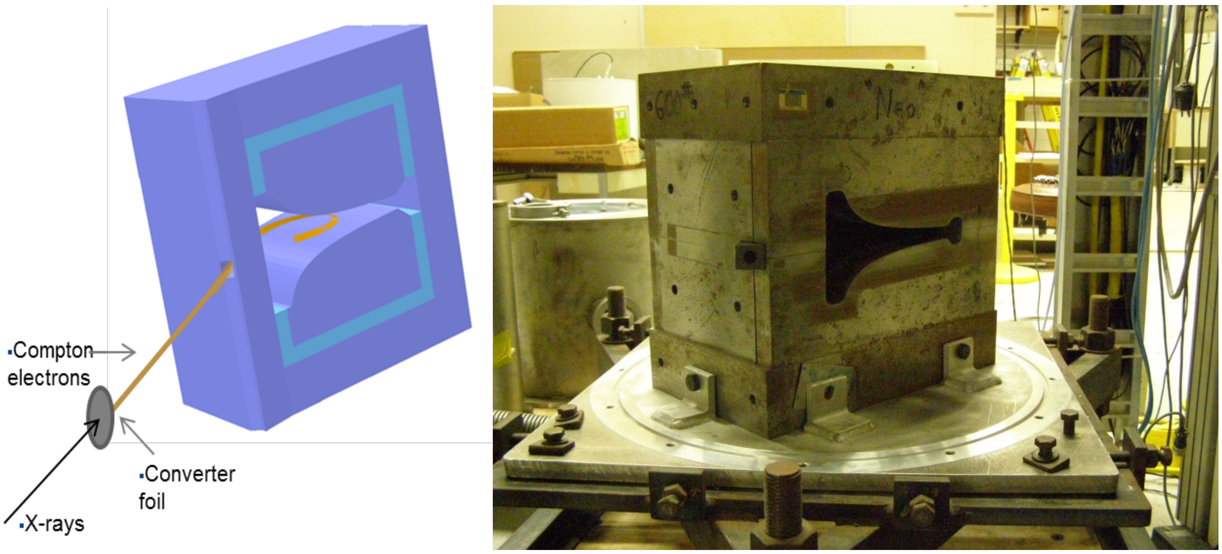

Figure 1. A schematic of the Compton spectrometer with x-ray and electron trajectories is shown at left. A photograph of the Compton spectrometer is shown at right.

The electrons enter the spectrometer through an opening of the mirror plane at an angle of 41°. The focal plane is located at the maximum displacement of the electrons from the magnet entrance. The position of the electrons is proportional to the square root of the electrons' momentum. The electron momentum, p, as a function of focal plane position, x, is given by the expression[1]

$$\text{p (MeV/c)} = \frac{Gx^2(cm)}{2x3.3356(1+\sin A)} \tag{1}$$

where A is the angle between the focal plane and incident beam (entrance angle) and G is the magnetic field gradient in kG/cm. The factor of two is due to the assumption of a quadrupole field[2,3], and 3.3356p is the magnetic rigidity in kG*cm. The energy range of the focal plane is from < 1 to 20 MeV. A slot in the upper magnet and pole piece gives access to the focal plane.

3. CALIBRATION EXPERIMENT: DATA AND RESULTS

The spectrometer was calibrated with a negative ion source[4] at the Special Technologies Laboratory of National Security Technologies, LLC in Santa Barbara, California. Beams of negative hydrogen and hydroxide ions were produced for the experiment. Details of the ion source construction and operation can be found in Ref. 4. The Compton spectrometer was placed in a vacuum can, and the entire system (spectrometer and ion source) operated at an average pressure of 1.4e-6 torr.

The accelerating voltage of the ion source was varied from < 1 kV to 45 kV in steps of minimum 10 V in order to change the momentum of the ions. The resulting ion beams were used to calibrate the focal plane over the momentum range of 1.5 MeV/c to 19 MeV/c. Six cylindrical brass "button" detectors were placed along the focal plane. Two different masks were placed in front of these electrodes. The masks are shown in Figure 2. The 1.5 mm wide slits of the first mask were centered over the detectors with a spacing of 2.54 cm and the first slit at 2.3 cm from the edge of the focal plane area accessible from the top slit. The second mask consisted of 1 mm slits shifted 4 mm in the higher momentum direction as compared to the slits of the first mask. In addition, 1 mm slits were added 2 mm from the center of the first four (lower momentum) electrodes in the opposite direction. The well-known position of the slits allowed the momentum calibration.

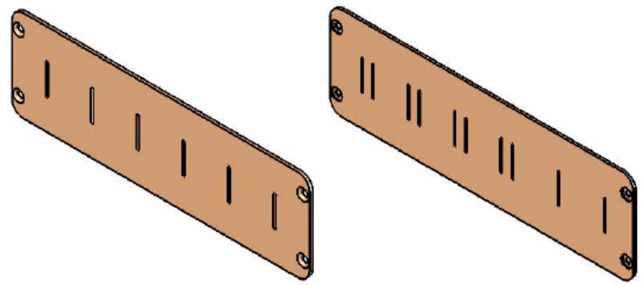

Figure 2. Mask 1 is shown at left. Each 1.5 mm slit is centered over a brass detector located in the spectrometer focal plane. Mask 2 is shown at right. Each pair of slits is -2 mm and +4 mm relative to the central slit of mask 1. The single slits are located before detectors 5 and 6, with the detectors numbered from low to high momentum. The single slits are +4 mm as compared to the central slits of mask 1. The slits of mask 2 are 1 mm wide.

Data from two sets of experimental conditions are shown in Figure 3. The first mask was placed in front of the focal plane detectors. Scans of electrodes #1-3 with H^- ions are shown in the left column and scans of electrodes #3-6 with OH^- ions are shown in the right column of Figure 3. The graphite collimator was not present in the upper set of measurements, and the graphite collimator was added in the lower set of scans shown in Figure 3. The narrower peaks of the lower set are likely due to the restricted angular acceptance.

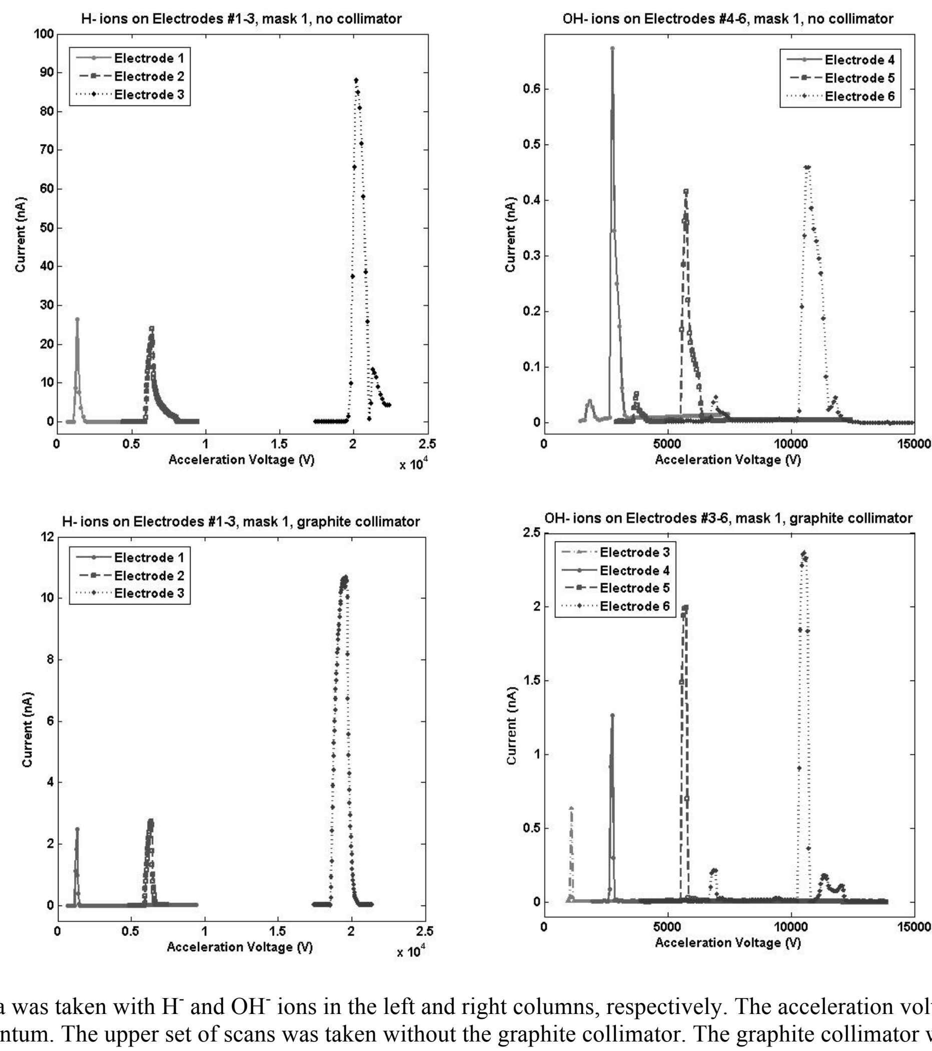

Figure 3. Data was taken with H^- and OH^- ions in the left and right columns, respectively. The acceleration voltage dictated the ion momentum. The upper set of scans was taken without the graphite collimator. The graphite collimator was inserted for the lower set of scans, which reduced the angular acceptance of the spectrometer.

A set of measurements with the second mask are shown in Figure 4. Data taken with H^- ions is once again on the left and the data taken with OH^- ions is on the right. The upper set was taken with the graphite collimator inserted. During the lower set of scans, the collimator was constricted to 7.4 mm in diameter by brass tape. The peaks do not become noticeably sharper due to the increased collimation. One possible explanation is inconsistent beam profile; the extraction and focusing voltages used to produce the beam varied among the scans. The effect of the angular acceptance on the resolution (peak width) on the focal plane is under further study.

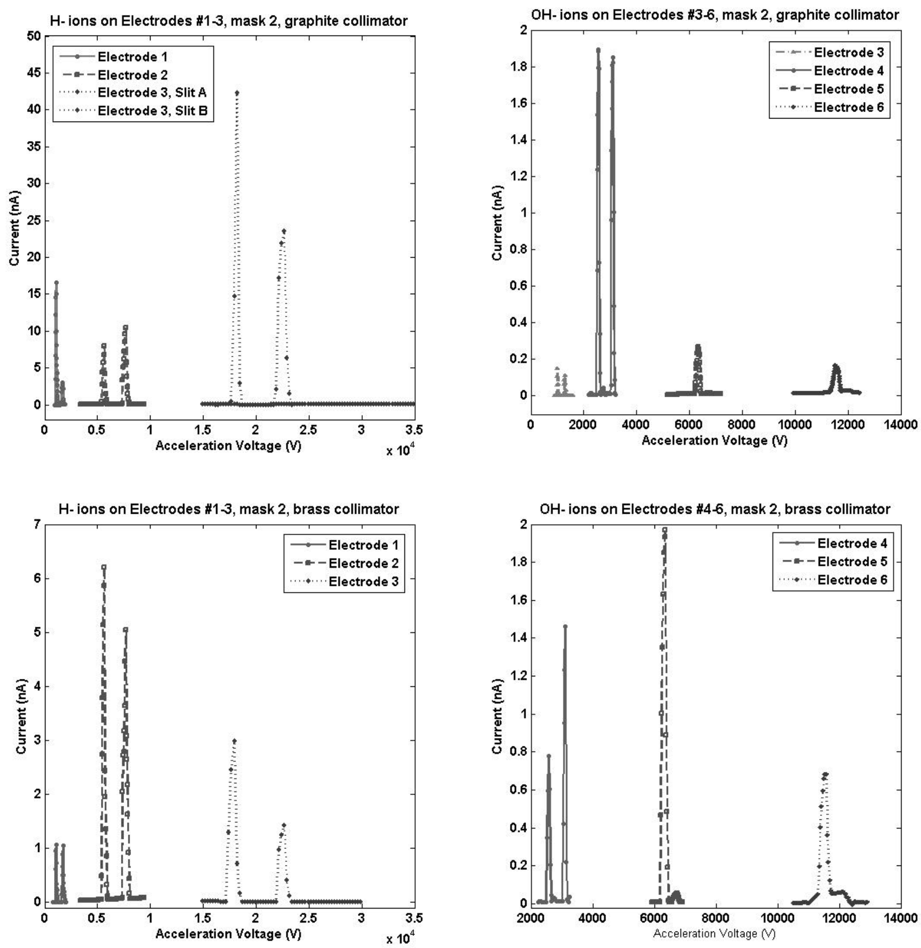

Figure 4. Data was taken with H^- and OH^- ions in the left and right columns, respectively. The upper set of scans was taken with the graphite collimator (diameter = 14 mm). Brass tape was placed over the graphite collimator for the lower set of scans, reducing the opening to 7.4 mm.

The relationship between the particle momentum and focal plane position was given in Equation 1. The square root of the ion's momentum, p, is proportional to the focal plane position, x, minus an offset, b, as shown in the simplified expression

$$p\ (\mathrm{MeV/c}) = C[x(cm) - b]^2 . \qquad (2)$$

A plot of the fit is shown in Figure 5. The data exhibits the predicted quadratic behavior, and the asymptotic intercept, b, was 32.5 ± 0.7 mm to the left of the accessible focal plane area.

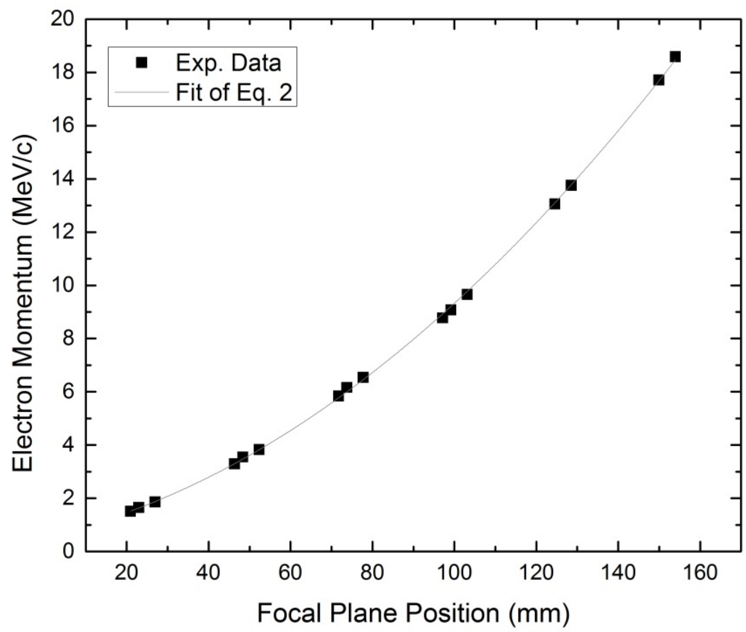

Figure 5. Preliminary fit of the electron momentum as a function of focal plane position.

4. SOURCE MEASUREMENTS: DATA AND RESULTS

A series of experiments were conducted at the Microtron, a bremsstrahlung source at LANL. The Microtron accelerates a continuous beam of electrons to one of the following four energies: 6, 10, 15, or 20 MeV. The electrons impinge upon a rotating target. The dose of 650-2400 rad/min at 1 m is relatively high compared to that of most flash radiographic sources. Endpoint energies of the bremsstrahlung spectra at the four energies were not known precisely, which provided the motivation for these experiments.

A thin vacuum window separated the vacuum can from atmosphere. The incident beam of x-rays was collimated down to ~2 mm before passing through the vacuum window and impinging upon the target. Three different targets were used in these experiments. Runs were conducted with a 0.5 mm aluminum target and with 0.5 mm and 0.7 mm beryllium targets. The ejected Compton electrons were forward-selected by the graphite collimator as the entered the spectrometer. A Kodak phosphor[5] was inserted into the focal plane. Sample images of two acceleration energies are shown in Figure 6. The white streaks on the images indicate the range of momentum of the electrons along the focal plane, and as expected the electrons from a 20 MeV run shown in Figure 6 (right) extend farther along the focal plane than the 10 MeV electrons shown in Figure 6 (left).

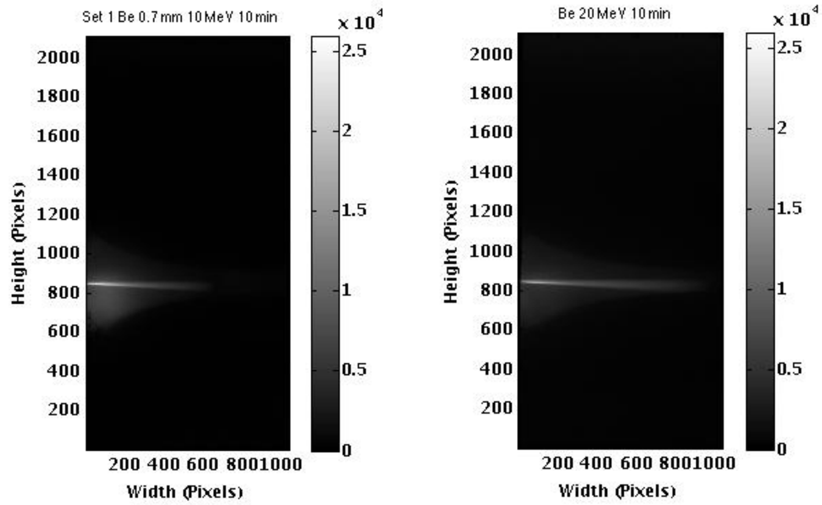

Figure 6. Sample images of phosphors. The exposure time was 10 minutes, and a 0.7 mm beryllium disk was the converter foil. The extent of electrons produced by 10 and 20 MeV runs is shown at left and right, respectively.

The intensity profiles in the region of interest of the phosphor images were summed and endpoint energy determined. A set of runs included a measurement at each acceleration energy. The endpoint energies for a set and the maximum predicted endpoint energies (an approximation equal to the acceleration voltage) are shown in Figure 7. The endpoint determination is preliminary, and the error analysis is not complete. The maximum energy of the Compton electrons was about 5-6% less than the expected energy of the electrons accelerated to produce the bremsstrahlung x-rays. Final analysis will include the conversion of Compton electron energy to photon energy, and the conversion of photon energy to accelerated electron energy. For the experiments in this section, the focal plane position was determined from the entrance of the spectrometer. In Figure 5, the focal plane position was measured from the edge of the plate inserted into the focal plane ~3 cm from the entrance of the spectrometer.

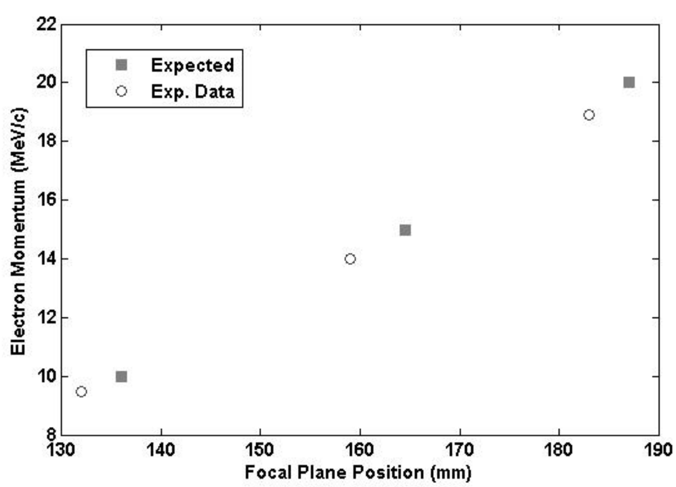

Figure 7. Comparison of the expected maximum position and momentum to the experimental data of a set of 0.7 mm beryllium target runs. The results are preliminary.

A first calibration of the spectrometer was attempted with a 9.5 Ci ^{60}Co source at LANL. The source was placed ~50 cm from the spectrometer entrance. The x-rays were collimated through a 5 mm diameter tungsten collimator, and the graphite was removed, widening the magnet opening into a 2 x 2 cm square. The collimation was opened in order to accept more x-rays; this change in experimental procedure resulted in decreased resolution at the focal plane. Several hours of exposure only resulted in a dose of ~40 rad on the target. A sample reconstructed ^{60}Co spectrum is shown in

Figure 8. The asterisks indicate the positions corresponding to 0.5, 1.17, 1.25, 1.33, and 2.5 MeV/c on the focal plane. The analysis of the ^{60}Co experiments is also in progress.

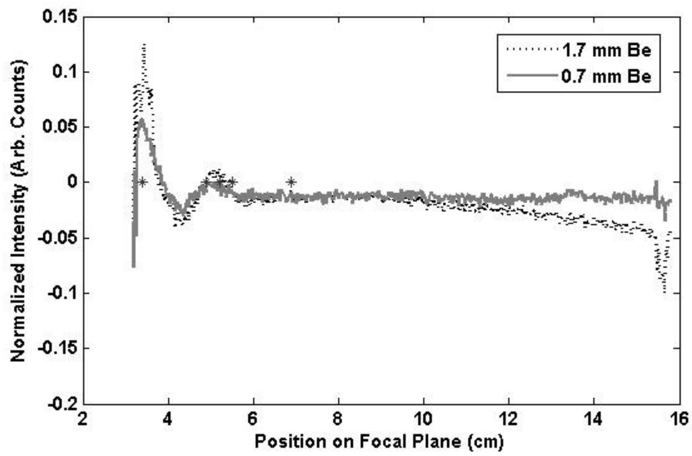

Figure 8. Co-60 reconstructed spectra. The asterisks indicate 0.5, 1.17, 1.25, 1.33, and 2.5 MeV/c. The solid and dotted lines indicate spectra obtained with 0.7 and 1.7 mm Be targets, respectively.

5. CONCLUSIONS

The neodymium-iron Compton spectrometer has been successfully re-commissioned. Calibration experiments were recently conducted, and the initial analysis has been completed. The spectra from a Co-60 measurement and series of bremsstrahlung measurements have been reconstructed. Further analysis of the calibration experiment will be conducted with a focus on determining the current resolution of the spectrometer. Experiments are planned in the near future at both DARHT and RITS-6. Two detector systems are in development – a time-integrated system that will consist of scintillator segments along the focal plane and a time-resolved system with a target resolution of less than 2 ns.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of many of our colleagues. We would like to thank David Barlow for mapping the magnetic field of the spectrometer, John Stearns for the operation of the Microtron, and Samuel Gonzalez and Timothy Dugan for their support and operation of the Co-60 source. We would also like to thank the following colleagues at STL: Tom Keenan for the engineering support, Glen Anthony for machining necessary parts, and Ben Valencia for the support table. We appreciate the many colleagues who lent equipment and who participated in many valuable discussions, especially George Morgan.

REFERENCES

[1] Morgan, G. L., King, N. S. P., Lisowski, P. W., Boyer, K. G., Enge, H. A., Kowalski, S. B., Holsinger, R. F., Lown, R. R., Iversen, S. G., Tinsley, J. R., and Baltrusaitis, R. M., "Broad range electron spectrometer using permanent magnets," Nucl. Instr. and Meth. A308, 544-556 (1991).
[2] Enge, H. A., "Achromatic Magnetic Mirror for Ion Beams," Nucl. Instr. and Meth. 162, 161-180 (1979).
[3] Enge, H. A., "Magnetic Spectrographs for Nuclear Reaction Studies," Rev. Sci. Instr. 34, 385-389 (1963).
[4] Trainham, R., Tipton, A. P., Bartsch, R. R., "Calibrating the DARHT Electron Spectrometer with Negative Ions," Report DOE/NV/25946--256 (2005).
[5] www.carestream.com